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Energy Input and HI Spin Temperatures in Low Pressure Regions

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We report on two recent (unpublished) HI emission/absorption studies, carried out with good sensitivity using the Arecibo 21cm beam. One study (Colgan, Salpeter and Terzian) looked for high velocity clouds of our own Galaxy in absorption in the directions of 63 of the brightest continuum sources reachable with the Arecibo telescope. HI emission mapping in the neighborhood of these directions was also carried out. The other study (Corbelli and Schneider) looked for absorption along lines of sight to about 50 weaker sources which pass within a few diameters of nearby disk galaxies. Neither study detected any absorption.

Three generalizations emerge from these and previous published absorption studies, as well as published emission mapping of high velocity clouds (HVC) and outer regions of disk galaxies. Qualitatively, at least, these properties are similar for HVCs and outer disks: (1) There is no evidence for any appreciable column densities of HI ($N_{HI} \gtrsim 5\times10^{18} cm^{-2}$, say) being "hidden" in emission studies by an extreme "subthermal effect" depressing the HI spin temperature T_S so far below the gas kinetic temperature T_K that it approaches the microwave background radiation temperature T_R. (2) While there is a wide dynamic range of values for N_{HI}, there is a tendency towards a "cut-off" on the lower end. One can state a related tendency for the (projected) shapes of iso-intensity contours: While the shapes of outer contours can be highly non-circular (e.g. irregular, long "plumes"), there is a tendency for fairly sharp intensity gradients near some lower "cut-off" value N_l of N_{HI}. For HVCs the column densities extend up to a few times $10^{20} cm^{-2}$ and N_l is of order a few times $10^{18} cm^{-2}$; for outer disks N_l is of order $10^{19} cm^{-2}$. (3) For column densities N_{HI} up to $\sim 10^{20} cm^{-2}$ one usually sees no HI absorption at all. For total column densities a few times larger one may find appreciable absorption over a narrow velocity range, but still none for most of the HI over a wider velocity range (see, e.g., Carili, van Gorkom and Stocke, Nature 338, 134 1989). Given the sensitivity for absorption studies, we see that most of the HI material for a column density of $N_{HI} \sim$ (1 or 2) $\times10^{20} cm^{-2}$ must lie at a spin temperature T_S above some measurement threshold of at least a few hundred K. We thus have to consider appropriate heat sources.

Presumably neither HVCs nor outer disks and plumes have supernova remnants or hot stars inside them, so the energy source must come from the outside. We consider first two simple extreme cases (a) A ubiquitous flux of penetrating ionizing radiation (cosmic rays or X-rays with $h\nu \gtrsim 150$ eV); (b) Some heat source, presumably coming from supernova energy release in the inner disk and moving upward and outward through a corona ("galactic fountain"), which ionizes only indirectly through collisions (e.g. hydrostatic waves, see Ferriere, Zweibel and Shull, Ap.J. 332, 984, 1988). For thermal equilibrium at an assumed pressure p and gas kinetic temperature T_K, the required energy input rate ε per H-atom is appreciably larger for (a) than for (b), because the electron density is larger and free electrons lead to larger radiative cooling losses. The "subthermal effect", the depression of spin temperature T_S below

T_K, depends on the Lyman-alpha pumping rate, which in turn depends on the ionizing flux and the column density; this depression is smaller for (a) than for (b). For $N_{HI} \sim$ (1 or 2) $\times 10^{20} cm^{-2}$, we have calculated the required values of ε for a number of assumed pairs of values of p and T_S; for most cases the first effect dominates the second, so that ε is larger for (a) than for (b). The dependence on p and T_S is complex, but at $p \sim 100 \times k \times cm^{-3} \times K$ and $T_S \sim$ (100 to 3,000) K we have roughly $\varepsilon \sim 3 \times 10^{-15} eV\ H^{-1} s^{-1}$ for case (a) (the dependence on p is less than linear). The ε required for case (b) is smaller by a factor between 0.1 and 0.5.

We return to the observational generalizations, numbered (1), (2), (3) above, in relation to different models: (1) states that $T_S - T_R$ is not very small for $N_{HI} \gtrsim 5 \times 10^{18} cm^{-2}$, say. This is not surprising theoretically--such an extreme subthermal effect would arise only for very small pressures ($p \lesssim 1 \times k \times cm^{-3} \times K$) and if there is little energy input beyond starlight and the minimum extragalactic X-ray background. A practical consequence, however, is that HI emission brightness temperature measurements always give N_{HI} (or an upper limit) correctly. (2) states that outer edges of HVCs and galactic disks or plumes tend to have sharp edges in N_{HI}, at some column density level N_l (between $\sim 2 \times 10^{18}$ and $10^{19} cm^{-2}$). This could have two types of explanations: (a) These structures could have been formed with sharp edges in total hydrogen (neutral plus ionized), although one would still have to explain why the edge has not broadened with time. (b) The edge could appear artificially sharp when viewed in HI because an ionizing flux or other energy input produces an ionized layer for column densities up to N_l. Because of the small value of N_l the pressure p, and hence the required flux, is quite uncertain. At these low column densities, "star-like" UV ($h\nu$ = 13.6 to about 50 eV) could play a role. Sufficiently powerful heat sources for observational generalization (3; see below) are probably also sufficient to ionize a column density of $\sim N_l$. In view of the likely strong heat sources (and the empirical fact 1 above) we need not consider the alternative of very low T_S hiding emission for $N_{HI} \lesssim N_l$.

(3) The minimum extragalactic cosmic ray and X-ray flux is not sufficient to keep spin temperatures above a few hundred K for a relatively thick layer with $N_{HI} \sim$ (1 to 2) $\times 10^{20} cm^{-2}$ (stellar UV photons with $h\nu < 50\, eV$ are irrelevant here since they could not penetrate). Fortunately, the uncertainty in the internal pressure is not very great in this case: Pressures must be appreciably smaller than in an inner galactic disk ($p \lesssim 10^3 k\ cm^{-3} K$, say) and must exceed that due to self gravity alone ($p \gtrsim 10k\ cm^{-3} K$ for $N_{HI} \sim 10^{20} cm^{-2}$). The required flux of cosmic rays or medium-soft X-rays ($h\nu \gtrsim 150\, eV$) impinging from the outside is of order 10^{-6} erg $cm^{-2} s^{-1}$. This is not ruled out, but would represent an appreciable energy requirement if it were a cosmologically uniform extragalactic diffuse flux; e.g., it is larger by a factor of order 10 than an extrapolation of the known power-law X-ray flux at $h\nu >$ 1 keV down to ~ 150 eV. The overall energy budget is of course less severe if the energy flux is not ubiquitous but comes from the individual galaxy through its corona in a "galactic fountain" (see Ap. J. 326, 551, 1988). If the energy carried in such a stream were primarily in the form of hydromagnetic waves, electron heat conduction and cooling flows, the energy required would probably be slightly less than for ionizing radiation (intermediate between cases a and b). If spread over a radius of about 30 kpc, such a stream would require ~ 5% of the total galactic supernova energy output rate.